

PERFORMANCE COMPARISON BETWEEN DIGITAL TWIN IEDs AND PHYSICAL DEVICES THROUGH CLOSED-LOOP TESTING

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Abstract

The availability of digital twins of protection and control devices provides improvements in commissioning processes, enabling testing before or during the substation implementation, resulting in significant time and money savings by reducing the need for physical testing and minimizing downtime. However, a critical challenge remains: ensuring that virtual twins accurately replicate the behavior of physical IEDs (Intelligent Electronic Devices). Without this validation, the reliability of using digital twins for protection setting verification is uncertain. This study addresses this gap by subjecting both real IEDs and their digital counterparts to a diverse set of test scenarios, comparing their responses to evaluate the accuracy and benefits of this technology.

1 Introduction

Digital twins are employed throughout a system lifecycle to simulate, predict, and optimize both the product and the production system before investing in physical assets and prototypes. For the protection of electrical systems, nowadays it is possible to configure virtual replicas of real IEDs through a virtual platform that enables automated testing by reproducing COMTRADE files.

The engineering and commissioning of a substation demand significant time and often can only be carried out after the substation equipment has been delivered. Now, testing can be conducted before or during the installation of the actual substation, enabling rapid verification of protection settings without the need for the real hardware. Protection devices connected via GOOSE (Generic Object Oriented Substation Event) or protection interfaces can also be simulated and tested, including their communication with each other.

When discussing digital twins, several questions arise about the behavior of these devices, such as: is the virtual IED a faithful copy of the real IED? Does it have the same behavior, algorithms, and functionalities? Are its responses identical to those of the physical device?

This work aims to answer these questions through practical test results. To carry out the comparisons, tests were carried out using both methodologies (the conventional method and the Digital Twin approach) on protection schemes applied to a

system with characteristics similar to those of the national transmission network in terms of voltage levels, typical transmission line geometry, and short-circuit levels, with a focus on line differential protection (87L).

2 Digital Twins

Digital Twin Models aims to be the exact virtual replicas of physical objects, systems, or processes. By leveraging real-time data, sensors, machine learning algorithms, and simulations, these models enable the analysis and prediction of the behavior of physical systems. The perfect relation between the digital twin and its physical counterpart provides deep insights into how the product or system operates under varying conditions, allowing for early fault detection, performance optimization, and predictive maintenance.

The importance of digital twins in product development is significant. They enable faster and more efficient innovation as engineers can test and iterate in a virtual environment before implementing changes in the real world, saving time and resources. Furthermore, with the ability to simulate different scenarios and operating conditions, companies can anticipate issues and adjust their products to improve durability, functionality, and customer satisfaction. This approach not only accelerates the development cycle but also reduces costs and minimizes risks, making it an essential tool in modern engineering and the management of complex operations.

A digital twin has to be seen as more than a simulation, which is merely a data-driven prediction of how a physical environment/process/person/product will behave. With continuous advancements in digital technology, digital twins are becoming more robust and increasingly vital for businesses. Generally speaking, a digital twin helps solve numerous challenges, such as:

- Reducing downtime: Planned or unplanned downtime can be costly for a company. With digital twin technology, businesses can be better prepared to address problems more quickly or avoid them altogether;
- Operational efficiency: Digital twins can reveal previously undetectable issues and guide managers to make data-driven improvements;
- Product enhancements: Product designers can use insights from digital twins to improve the product in future iterations or identify opportunities for new product lines or features based on product usage data.
- Improving customer experience: Digital twins can be used to deliver new experiences and features to customers;
- Optimizing service capabilities: Supporting service technicians and customers with augmented reality guidance for remote specialized assistance or improved first-time resolution rates;
- Consistent product quality: Since digital twins have a physical counterpart, operators can view detailed data and insights, identify patterns, and proactively address quality or service issues.

In the field of electrical system protection, digital twin technology has been applied to protection devices, known as IEDs. The concept of a virtual IED (a digital twin of a physical device, including algorithms, functionalities, and communication interfaces) enables commissioning services to be carried out in a digital environment without the need for physical IEDs or testing equipment.

The virtual IED offers time savings at various stages:

- Implementation: Planning and adjustments;
- Commissioning: Factory acceptance testing (FAT) and site acceptance testing (SAT);
- Operation: Device handling;
- Training: Flexible access to the device anywhere;
- Maintenance and Services: Fault analysis.

This paradigm shift, through testing on virtual devices, also creates a new demand for testers who are no longer tied to specific hardware. With fully digital data generation and acquisition, testing is no longer limited by the number of analog outputs or binary inputs on hardware, allowing simultaneous testing of multiple bays and the evaluation of selectivity.

Testing protection in a fully virtual environment can bring numerous benefits [1], such as:

- Faster energization of new systems due to shorter

execution timelines;

- Reduced OPEX (Operational Expenditure) with shorter interruptions, leading to increased availability;
- Lower CAPEX (Capital Expenditure) for testing equipment;
- Rapid remote support with fault analysis, easily reproducing the behavior of products and systems;
- Flexible, continuous, and customized training in a virtual testing environment based on real system conditions.

In this work, simulation software for electromagnetic transients was used, capable of performing automated tests on virtual IEDs.

3 Simulation Software

The EMT (Electromagnetic Transient) simulation software [2] was designed primarily to enable users to model complex power and control systems and simulate electromagnetic and electromechanical transients. In addition to performing simulations, the software allows signal playback/acquisition through test sets and virtual IED platform.

Digital input signals can be used to feedback into the simulation through multiple step-based process executed recursively. In this approach, signals are applied, for example, to modify the simulation due to the opening and closing of circuit breakers or other circuit points involving digital logic. This signal generation and acquisition process involves automatic stage overlapping with circuit feedback, creating a step-based closed-loop system with excellent results. It is worth noting that this methodology is only possible due to the reproducibility of IED trips, which ensure high accuracy in signal acquisition and processing. Moreover, the effectiveness of the step-based method for closed-loop testing has been compared with real-time simulation methodologies [3, 4], demonstrating that the results of protection device tests are identical for both methods.

The EMT simulation software can be used in a test system that combines software and hardware, with the capability to accurately model all electrical system components, including transmission lines. The tool allows the reproduction of very high-frequency waveforms (1 nanosecond time step), along with the fundamental frequency, at secondary levels. This meets all the necessary requirements for evaluating devices with traveling wave-based algorithms [5, 6].

4 Case Studies

In order to perform the comparisons as in [7] for the process bus, tests were conducted using both methodologies (conventional method and Digital Twin) on the protection schemes implemented in a system with characteristics similar to those of the Brazilian basic grid. These characteristics include voltage levels, the typical geometry of the transmission line, and short-circuit levels, focusing on line differential protection (87L). The modeled circuit is shown in Figure 1 and

includes two substations represented by their equivalent systems. A transmission line (500 kV class) was modeled between the substations, and at the line terminals, instrument transformer groups (CTs and VTs) and circuit breakers were

included. In this study, these were provided by line protection IEDs manufacturer [8].

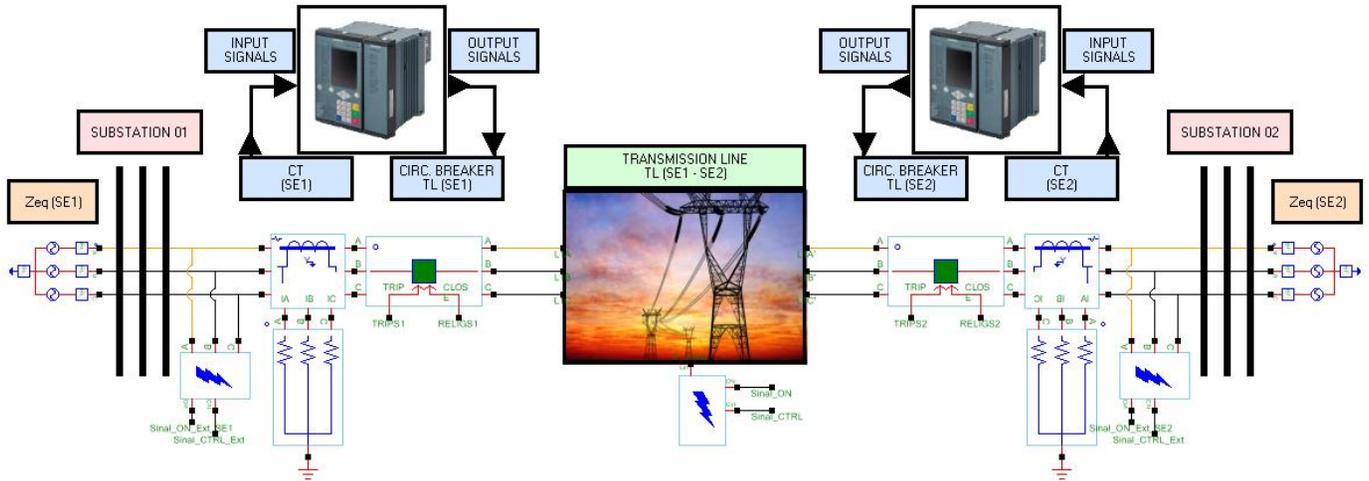


Fig. 1 - Power circuit modeled in EMT simulation software.

In the conventional test, the EMT simulation software performs the simulation of the modeled system by injecting the analog and digital signals, designated for this purpose within the software environment, to the test set [9]. Once this is done, the test set reproduces the signals (voltages, currents, and binary signals) and applies them to the line protection relays. Simultaneously, the binary outputs of the IEDs are acquired to be considered (e.g., for breaker opening or closing) in the subsequent iteration. All connections between the test set and the relays in this methodology are made through physical

cabling. In the virtual environment, however, the test set is no longer required, and the real IEDs are replaced by their digital twins. The signal flow is carried out through an API. Figure 2 illustrates the signal flow for both methods.

The developed system was subjected to a total of 260 test scenarios, where various fault conditions were simulated, varying the type of fault, angle of incidence and location, to verify the proper functioning of the protection system. Table 1 briefly describes the evaluated scenarios.

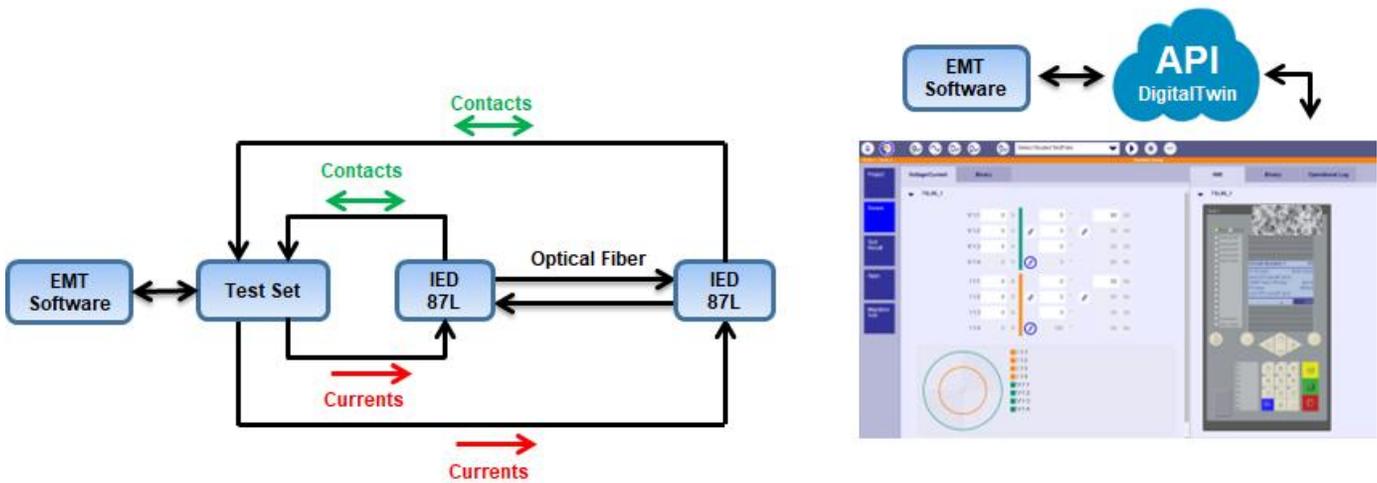


Fig. 2 - Conventional versus virtual methodology

Table 1 - Description of tests performed.

Cases	Case Description
50	Internal faults with incidence angles of 0° and 90° and tripolar reclosing with and without success. Faults will be simulated at: 0%, 25%, 50%, 75%, and 100% of SE1-SE2. Different types of faults will be simulated at each location.
50	Evolving internal faults with incidence angles of 0° and 90° and tripolar reclosing with and without success. Faults will be simulated at: 0%, 25%, 50%, 75%, and 100% of SE1-SE2. Different types of faults will be simulated at each location. The evolution occurs 1 cycle after the fault initiation.
30	Internal faults with fault resistance variation, at the line midpoint, to assess the influence on the differential protection operation. Fault incidence angles of 0° and 90° will be considered, adjusting the fault resistance with values varying from 5 Ω to 200 Ω. Tripolar reclosing with success will be verified for this case.
10	External faults at SE1 and SE2 entries, with incidence angles of 0° and 90°. For these cases, the non-operation of the 87L function must be verified. Different types of faults will be simulated at each substation.
40	External faults at SE1 and SE2 entries with saturation and incidence angles of 0° and 90°. For these cases, the non-operation of the 87L function must be verified. Different types of faults will be simulated at each substation for varying burden resistance values to induce light and heavy saturation.
10	External faults followed by internal faults, with incidence angles of 0° and 90°. For these cases, tripolar reclosing without success must be verified. Different types of faults will be simulated at each substation, with the internal fault initiated 6 cycles after the start of the external fault.
40	External faults with saturation followed by internal faults, with incidence angles of 0° and 90°. For these cases, tripolar reclosing without success must be verified. Different types of faults will be simulated at each substation, with the internal fault initiated 6 cycles after the start of the external fault. Light and heavy saturation will be induced by varying burden resistance values.
12	Internal faults under "switch on to fault" conditions. For these cases, the operation of the SOTF function after line energization attempts must be verified. The tested conditions will be: SOTF with SE1 terminal open: 0% and 100% of SE1 and SOTF with SE2 terminal open: 0% and 100% of SE1.
10	Verify relay response for underfrequency and overfrequency (57 Hz and 72 Hz). Apply various types of faults at 50% with fault incidence angles of 0° and 90°. Tripolar reclosing without success will be verified for this case.
8	Faults without communication, internal at positions 0% and 100%, as well as external faults. Apply faults with incidence angles of 0° and 90°. Overcurrent protection (emergency) operation and reclosing in unsuccessful mode must be verified for this case.

5 Comparison

For the purpose of exemplifying the comparisons carried out, the results obtained in the case of an AT fault at 0% of the transmission line, with an incidence angle of 0°, were used, simulating an unsuccessful reclosure.

Table 2 demonstrates a comparison between the two methodologies based on the results obtained from repeatability tests (20 repetitions), focusing on the operation times of the relay protection functions, thus confirming the equivalence of both in this regard. According to Table 2, it can be observed that the differences in the average operation times before reclosing range from 3 ms to 4 ms, which correspond exactly to

the delay time of the output relay of the IED. After reclosing, there is an increase in the values, which is justified by the lower precision of the IED timer in measuring the reclosing time. Although this results in small time differences, they lead to distinct reclosing moments, generating different re-energization transients. In other words, other levels of transient currents will be read by the IED, resulting in different operation times.

Table 2 - Comparisons of the operating times in milliseconds of the protection functions of the IEDS.

SYSTEM SIGNAL		ANALOG				VIRTUAL (DIGITALTWIN)				Δ Tmean. (ms)
		Tmin. (ms)	Tmean. (ms)	Tmax. (ms)	σ	Tmin. (ms)	Tmean. (ms)	Tmax. (ms)	σ	
TRIP (7SL86_1)	BR	11,800	14,182	17,250	1,59	8,050	10,473	12,050	1,28	3,71
	AR	12,450	16,480	20,800	2,64	12,950	15,330	17,950	1,67	1,15
SOTF (7SL86_1)	BR	-	-	-	-	-	-	-	-	-
	AR	14,200	20,100	26,200	2,88	12,950	16,128	19,950	2,24	3,97
REC_79 (7SL86_1)		1032,4	1035,6	1039,9	2,25	1029,8	1031,7	1033,8	1,57	3,91
TRIP (7SL86_2)	BR	12,600	14,540	17,600	1,54	8,050	10,320	12,050	1,38	4,22
	AR	13,100	17,157	23,150	3,38	12,950	15,725	19,000	1,81	1,43
SOTF (7SL86_2)	BR	-	-	-	-	-	-	-	-	-
	AR	15,750	22,950	29,950	4,19	12,950	16,168	19,950	2,41	6,78
REC_79 (7SL86_2)		1031,3	1033,1	1035,2	1,16	1034,0	1036,4	1038,1	1,27	3,29
<p>Tmin. → Minimum signal operation time across all repetitions; Tmax. → Maximum signal operation time across all repetitions; Tmean. → Average of signal operation times across all repetitions; σ → Standard deviation of signal operation times across all repetitions; ΔTmean. → Difference between the average times obtained in the real-time simulator and the iterative simulator; BR → Occurrence before reclosure; AR → Occurrence after reclosure;</p>										

The setups of the systems used for the tests, both with the conventional methodology and in the virtual environment, are shown in Figures 3 and 4, respectively. These figures

demonstrate the portability of the tool, which allows for real field tests and virtual environment testing anywhere as long as an internet connection is available.

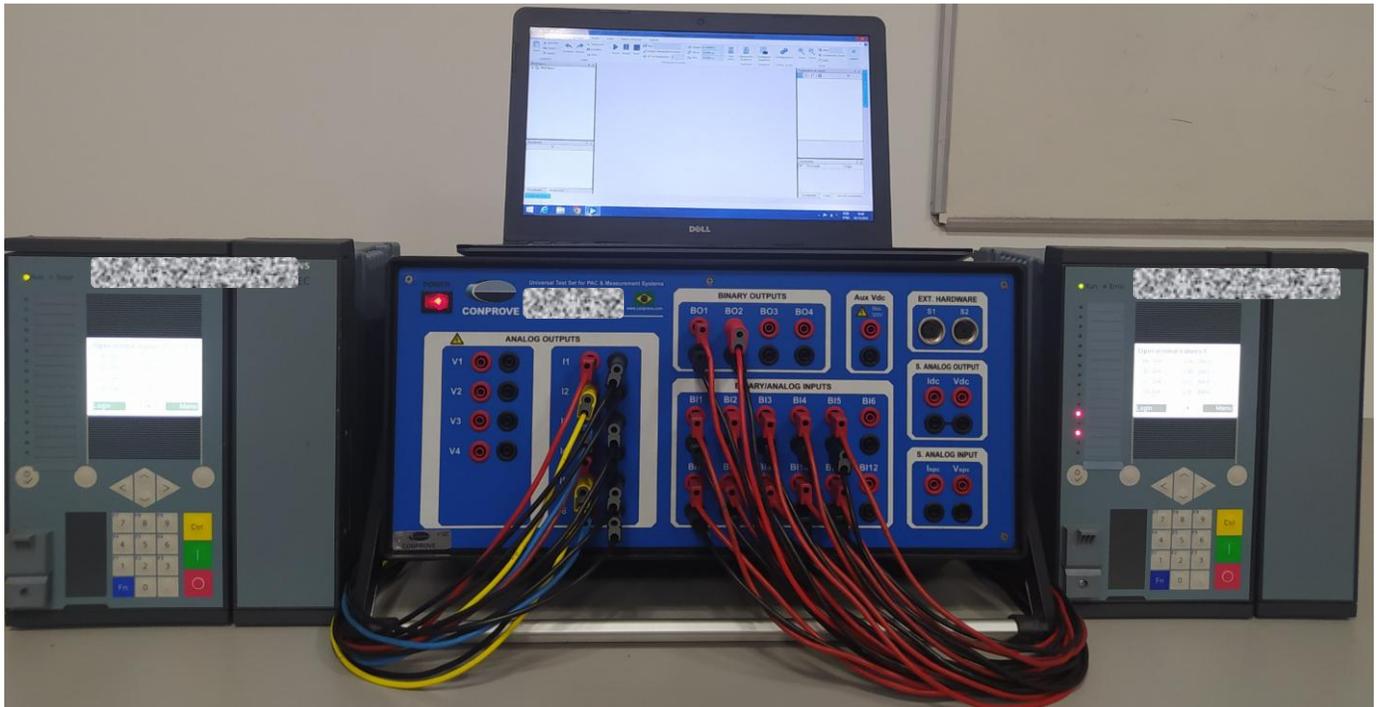


Fig. 3 - Conventional methodology.

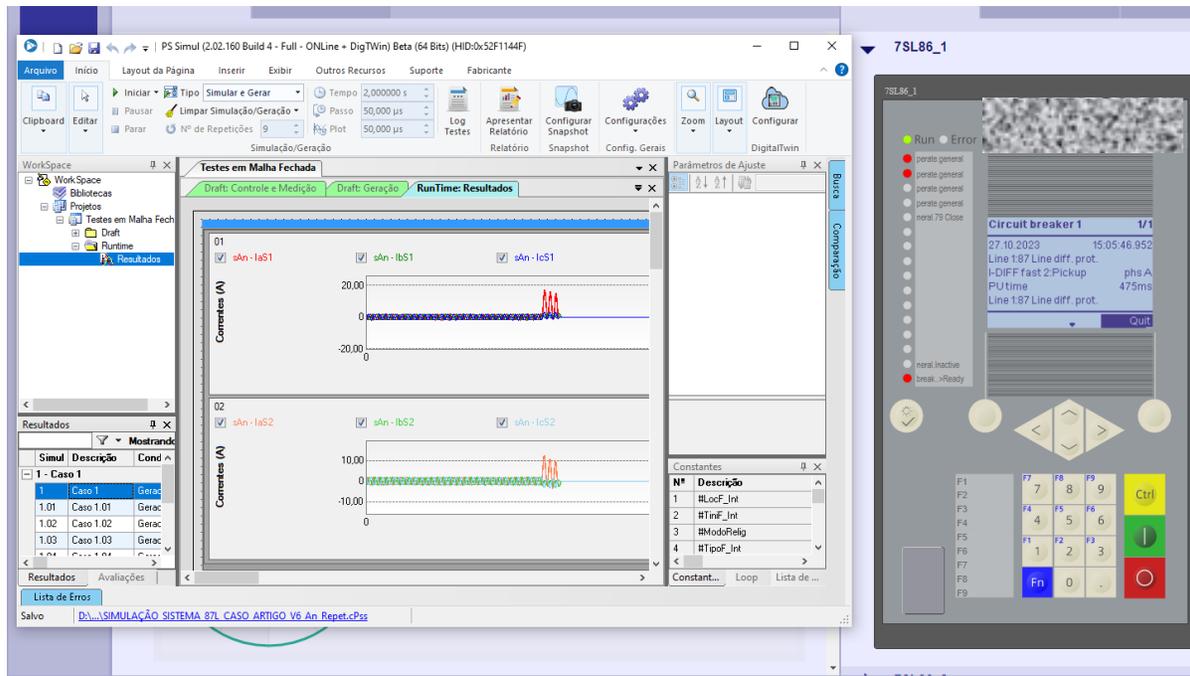


Fig. 4 - Virtual environment.

6 Conclusions

The creation of digital twins enables testing in a controlled and safe environment, eliminating the need to interfere with the actual system. As IEDs continue to evolve in processing speed, communication protocols, and automation capabilities, testing tools must also advance. Incorporating virtualization and automation technologies enhances their ability to evaluate modern protection systems. Advanced tools with virtualization capabilities not only reduce costs and risks but also provide significant flexibility for various testing scenarios.

This study compared the test results of commercial IEDs and their digital twins by simulating 260 contingency scenarios. The comparison focused on verifying the consistency between the behaviors of virtual and real IEDs. The evaluation considered operation times, specifically the time from the start of the fault to the issuance of a trip command. Results indicated that variations in operation times were primarily due to the switching mechanisms in physical IEDs, which do not exist in the virtual environment. This demonstrates that the protection logic and algorithms remain consistent across both methodologies.

Additionally, the study showcased a highly efficient and portable tool for closed-loop testing. Unlike traditional real-time simulation systems, this tool offers a cost-effective alternative for protection testing. Since it does not require connected hardware, it eliminates constraints related to the number of generation channels and the physical limits of voltage and current. This flexibility makes it a valuable solution for testing modern protection systems.

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